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Influence of covering on critical thickness of strained $In_xGa_{1-x}As$ layer

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Abstract

We examined the critical layer thickness (CLT) of mismatched epitaxial layers and strained heterostructures. Samples consisting of $In_xGa_{1-x}As/InP$ and $In_{0.52}Al_{0.48}As/In_xGa_{1-x}As/In_{0.52}Al_{0.48}As/InP$ were grown on InP substrates by metalorganic vapour phase epitaxy (MOVPE). The atomic force microscopy (AFM) was used to observe misfit dislocation generation. When the layer is buried in the heterostructure, its critical layer thickness increases. Our investigations have shown how many times this value may be exceeded in chosen technological conditions. A model was proposed, which explains difference between CLT of InGaAs with free surface and CLT of buried InGaAs. Heterostructures mentioned above were employed for producing InAlAs/InGaAs/InP HEMT transistors.

Keywords: Metalorganic chemical vapour deposition; Atomic force microscopy; Lattice parameters; Stress

1. Introduction

Ternary alloys are of increasing interest for both electronic and optical devices, such as heterojunction bipolar transistors, high electron mobility transistors, high-speed switching lasers, solar cells. Much work has focussed on the $In_{0.53}Ga_{0.47}As$ alloy because it can be grown lattice matched to the InP substrate. The use of mismatched epitaxial layers allows much greater freedom in designing heterostructure devices with desired characteristics.

If the lattice mismatch between the epilayers and substrate is small and the layer is thin, the mismatch is accommodated by strain in layer. In the case, when the mismatch or the layer thickness is increasing, the formation of misfit dislocation at substrate–layer interface is energetically favourable. However, lattice relaxation via misfit dislocation degrades the structural, electrical and optical epitaxial layer quality.

The point at which misfit dislocation starts to form is called the critical layer thickness (CLT), d_C. Although several theories have been proposed to predict critical value [1,2] in their work most authors [3,4] based on Matthews and Blakeslee model. Following equation arises from their model and it describes critical layer thickness [5]:

$$d_C=\left(\ln\frac{d_C}{b}+1\right)\frac{b(1-\nu\cos^2\alpha)}{2\pi\frac{\Delta a}{a}(1+\nu)\cos\lambda} \quad (1)$$

where: $b=\frac{a}{\sqrt{2}}$ is Burgers vector, a is the lattice constant, ν is the Poisson ratio, α is the angle between the dislocation lines and its Burgers vector, λ is the angle between the slip direction and that direction in the layer plane which is perpendicular to the line of intersection of the slip plane and the interface, and $\frac{\Delta a}{a}=\frac{a_W-a_P}{a_P}$ is the lattice mismatch.

Several groups [6,7], however, reported exceeding of the critical value obtained from Eq. (1). Besides, it follows from a strain compensation technique, which is often used to reduce net strain [8], that critical layer thickness with free surface has to be smaller than the CLT of the buried one. Experimental investigations of these differences were realised.

We studied critical thickness of covered layer and layer with free surface using atomic force microscopy as a characterization tool. In this paper we show that $In_xGa_{1-x}As$ layer with 1.3% lattice-mismatch in spite of

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exceeding the critical layer thickness defined by Mathews and Blakeslee, can be used as a pseudomorphic channel layer in HEMT structures. We measured, by the Van der Pauw method, not only the channel layer lattice relaxation but also electrical parameters of HEMT structures with different channel thickness.

2. Experiment

Heterostructures were grown by low pressure metalorganic vapour phase epitaxy LP-MOVPE on semi-insulating (100) InP:Fe substrates. A horizontal quartz reactor (AIX 200) and IR heated graphite susceptor were used. Trimethylgallium (TMGa), trimethylindium (TMIn), trimethylaluminum (TMAl) and arsine AsH_3, phosphine PH_3 were used as III and V group elements precursors with palladium-purified hydrogen carrier gas. During the structure growth, the reactor pressure and temperature were maintained at 100 mbar and at 650 °C, respectively. The V/III ratio was unchanged and amounted to 172. Samples were divided in to two groups (there were four samples with different InGaAs thicknesses in these groups): with free surface and covered by InAlAs layer. The first group consisted of (from bottom to top) an undoped InP buffer on InP:Fe substrate and an $In_xGa_{1-x}As$ strained layer ($x=65\%$). The second group of samples consisted of HEMT structures. An undoped InP buffer layer was first grown on InP:Fe substrate. A 10 period $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ superlattice and 10 nm $In_{0.52}Al_{0.48}As$ layer were subsequently deposited as the buffer. Finally, an $In_{0.65}Ga_{0.35}As$ channel layer (with different thickness' between samples), 4 nm $In_{0.52}Al_{0.48}As$ spacer, delta-doping Si donor layer and 20 nm $In_{0.52}Al_{0.48}As$ Schottky layer terminated the structure growth. In order to measure electrical parameters of these structures by the Van der Pauw method, the contact layer was not deposited. Growth interruptions of approximately 10 s were used at the interfaces between the $In_{0.65}Ga_{0.35}As$ channel and $In_{0.52}Al_{0.48}As$ layers to provide sufficient time for the growth surface of the channel layer to become smooth. It resulted in an improvement of interfaces quality and high electron mobility [9].

The growth rate of mismatched layer is equal to $r=5.87$ Å/s. It was determined by two techniques: secondary ion mass spectrometry (SIMS) to record the Ga element depth profile and a profilometer to measure of this value.

The structural properties of an $In_{0.65}Ga_{0.35}As$ mismatched layer with free surface and covered by an $In_{0.52}Al_{0.48}As$ layer were investigated by atomic force microscopy (AFM). AFM observations were made in air at room temperature with a Digital Instruments Nanoscope III using large field head. The investigation of sample surfaces allowed us to notice the onset of misfit dislocation generation, which correspond to the experimental critical layer thickness.

3. Results and discussion

3.1. Samples with free surface of $In_{0.65}Ga_{0.35}As$ layer

The $In_{0.65}Ga_{0.35}As$ layers with various thickness (23.4 Å, 70.2 Å, 103.4 Å, 125 Å) were characterised by AFM. Fig. 1 shows AFM images of strained (a) and relaxed (c) $In_{0.65}Ga_{0.35}As$ layers surfaces with different thicknesses (intermediate variant was missing).

The surface of the strained $In_{0.65}Ga_{0.35}As$ layer has a regular and straight monolayer step (two-dimensional growth mode). The average interstep distance is 200 nm and surface roughness is 3.5 Å (Fig. 1a). With increasing layer thickness, two-dimensional islands growth mode succeeded in two-dimensional growth, what is shown on the grown surface (Fig. 1b). As the thickness increases further, the elastic strain energy builds up to the point, where it becomes energetically favourable to form misfit dislocation at the interface. Finally, at a thickness of 125 Å, misfit dislocation lines can be seen on the layer surface (Fig. 1c). Hence the experimental critical layer thickness is equal to 100 Å for $In_{0.65}Ga_{0.35}As$ layer, while the critical value evaluated from Mathews and Blakeslee Eq. (1) is 68 Å. It is approximately 1.5 times greater than theoretically predicted, but it is too small to use this layer as an active range in HEMT structure (because of carrier confinement) with various thickness of $In_{0.65}Ga_{0.35}As$ channel (60 Å, 120 Å, 180 Å, 235 Å, 470 Å). However, several authors [9,10] have reported excellent properties of electronic devices from heterostructures with $In_xGa_{1-x}As$ and InAlAs layers exceeding Mathews and Blakeslee limit and experimentally determined the value. To investigate these discrepancy, HEMT structures with various thickness $In_{0.65}Ga_{0.35}As$ layer as a channel were grown.

3.2. Samples with covered $In_{0.65}Ga_{0.35}As$ layer

Surfaces of HEMT structures with various thicknesses of $In_{0.65}Ga_{0.35}As$ channel (60 Å, 120 Å, 180 Å, 235 Å, 470 Å) were observed using AFM. Selected images are shown in Fig. 2.

In Fig. 2a,b a strained heterostructure case is shown. The thickness of channel layer is above the Mathews and Blakeslee limit and is equal to 180 Å. Straight, parallel terraces with width and step high of 342 nm and 4.3 Å (in measured point), respectively, are shown on this sample. Surface roughness is approximately 1.5 Å. The relaxed structure with a 235 Å channel InGaAs layer is shown in Fig. 2c. Misfit dislocations appeared at the interface and dislocation lines can be seen on the

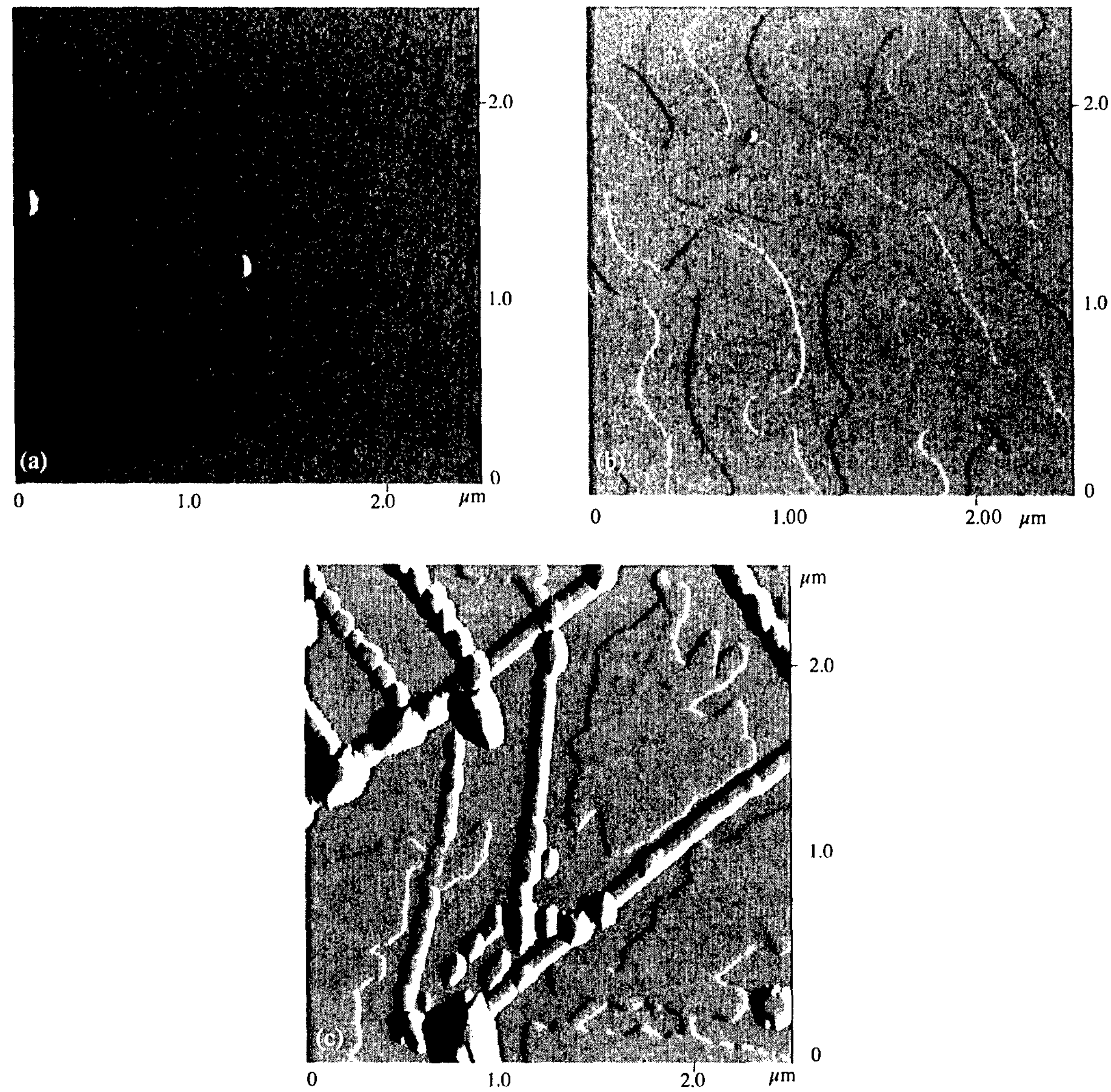

Fig. 1. AFM image of $In_{0.65}Ga_{0.35}As$ layers surface with their different thickness: (a) 23.4 Å, (b) 103.4 Å, (c) 125 Å.

sample surface. The critical channel thickness covered by InAlAs layer was determined as an average value between thicknesses in strained and relaxed cases. It equals 200 Å and it is three times greater than the value predicted by Mathews and Blakeslee theory and twice greater than experimentally specified thickness of strained InGaAs layer with free surface. To explain these discrepancy, a model, schematically presented in Fig. 3, was proposed.

Elementary cells of strained $In_xGa_{1-x}As$ layer mismatched to the InP lattice, covering InAlAs layer and InP substrate are illustrated by different size squares.

In a non-distorted state (Fig. 3II), the lattice parameter of a covered InAlAs layer a_{cap} equals to one of substrate (buffer) a_S and it is smaller than lattice constant of a strained $In_{0.65}Ga_{0.35}As$ layer.

In a coherent lattice state, in heterostructure layers interact forces, which are proportional to their thickness. We make an assumption that the lattice substrate does not deform because of its greater thickness than one layer.

The interaction between the covering layer and the mismatched one boils to the extent of covering materials lattice and to compress net of the mismatched layer (Fig. 3II). As a result of this interaction, lattice mismatch between a substrate InP lattice and strained $In_{0.65}Ga_{0.35}As$ layer covered and compressed by $In_{0.52}Al_{0.48}As$ layer results in being smaller than lattice mismatch one without covering $In_{0.52}Al_{0.48}As$ layer, (Fig. 3III and I). It is known that decreasing of a strain in a material lattice, the critical layer thickness is increasing.

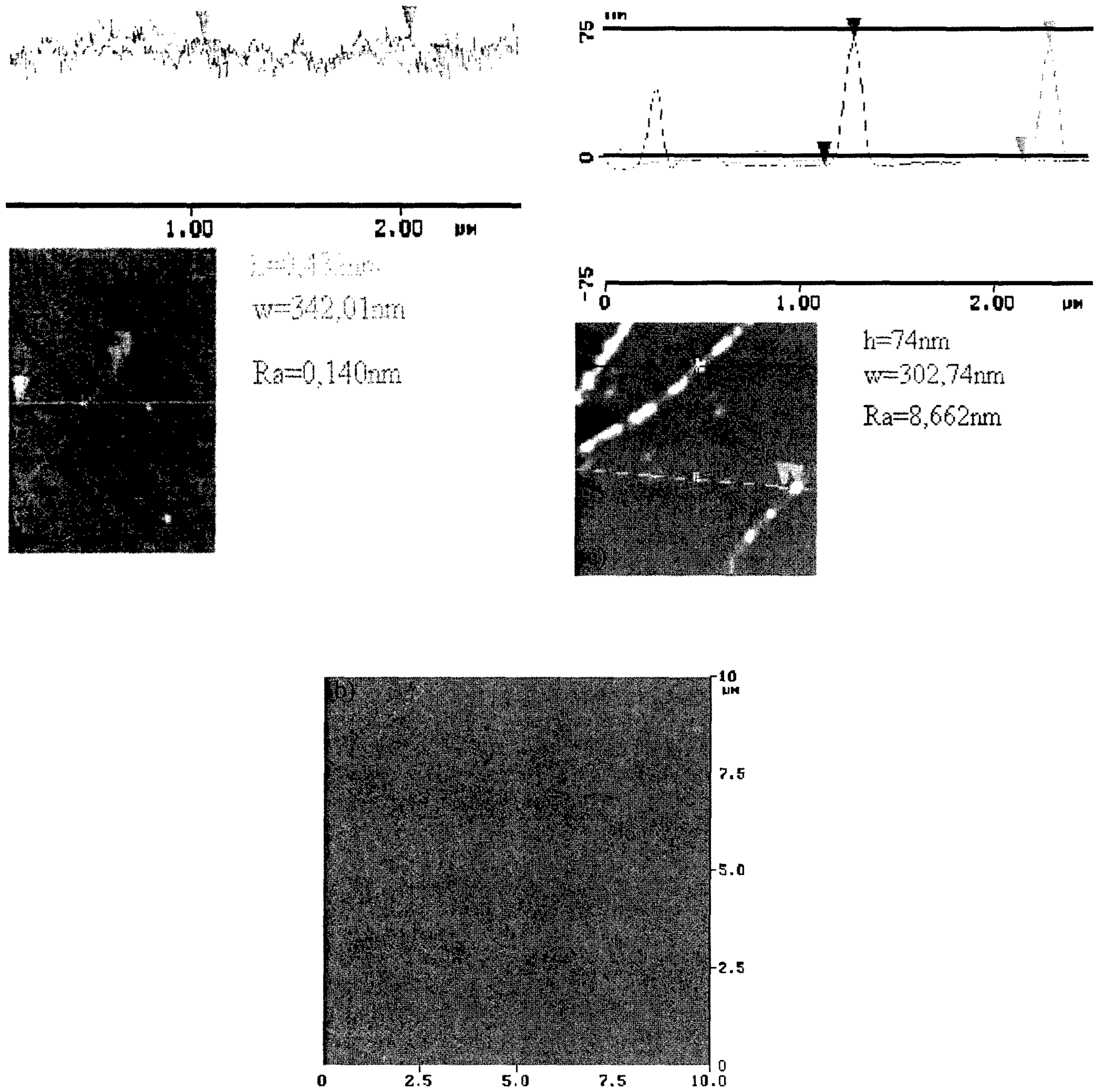

Fig. 2. AFM images of HEMT surfaces with different channel thickness: (a) 180 Å, (b) 180 Å, (c) 235 Å.

This model is working correctly beyond some thickness of covering layer. Above this value, $In_{0.52}Al_{0.48}As$ become to be an undeformable material.

Electrical parameters of HEMT structures were obtained by Van der Pauw measurements and placed in Table 1.

To make a comparison parameters of pseudomorphic HEMT structures to parameters of HEMT with a matched $In_{0.53}Ga_{0.47}As$ channel, the structure 955 was grown. Not fully carrier confinement to an active region is the reason for reduction of parameters beyond the thickness of 18 nm. Degradation of lattice correctness and larger contribution of an interface roughness in carrier scattering cause decreasing electron mobility with going up channel thickness. A 1090 HEMT structure with the channel thickness equal to 18 nm has the best electrical parameters. Above heterostructures were applied for producing InAlAs/InGaAs/InP HEMT tran-

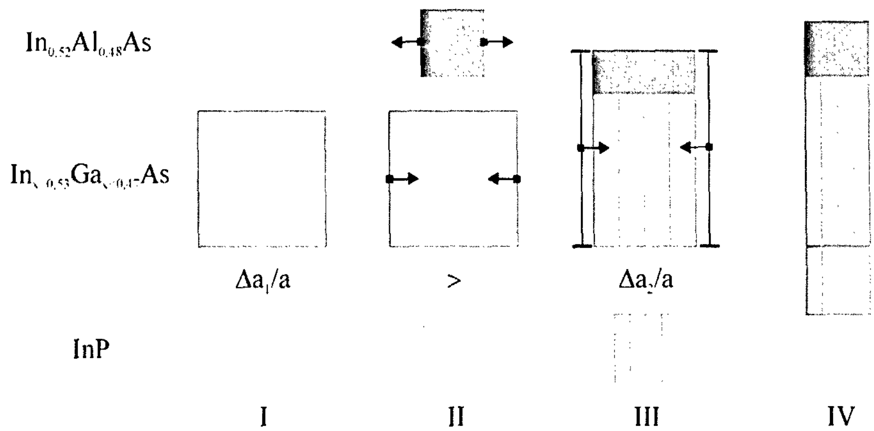

Fig. 3. Schematic diagram describing the decrease of lattice mismatch as a result of interacting a strain layer with a covering layer.

Table 1
Electrical parameters of HEMT structures

N°P	x (%)	Thickness (nm)	Electrical parameters of HEMT structures			
			n_{300K} (cm^{-2})	μ_{300K} ($cm^2\ Vs^{-1}$)	n_{77K} (cm^{-2})	μ_{77K} ($cm^2\ Vs^{-1}$)
955	53	20	2.22×10^{12}	8179	2.37×10^{12}	37 898
1599	65	6	5.1×10^{11}	2170	6.1×10^{11}	18 998
1606	65	12	2.7×10^{12}	6667	2.2×10^{12}	43 211
1090	65	18	1.9×10^{12}	9998	2.1×10^{12}	55 100
1607	65	23.5	3.3×10^{12}	5805	2.9×10^{12}	41 001
1608	65	47	2.1×10^{12}	4059	2.0×10^{12}	28 756

Table 2
The critical thickness of strained $In_{0.65}Ga_{0.35}As$ layer

Layer	The critical thickness of strained $In_{0.65}Ga_{0.35}As$ layer (nm)			
	d_{MB}	d_{FS}	d_{CS}	d_{CS}/d_{MB}
$In_{0.65}Ga_{0.35}As$	6.8	10.34	20.0	2.94

sistors. Their characteristics are presented in Nawz et al. [10].

4. Conclusion

We have investigated the impact of covering InAlAs layer on the critical thickness of strained InGaAs layer grown by MOVPE on InP substrate. Using AFM, we determined the critical thickness of InGaAs layer with free surface and covered by a 25-nm InAlAs layer and we compared with the Mathews and Blakeslee limit. Obtained parameters are shown in Table 2.

The critical thickness of the strained $In_{0.65}Ga_{0.35}As$ layer covered by InAlAs is approximately three times greater (2.94 times) than the value obtained from the Mathews and Blakeslee formula. To explain this discrepancy, a model was proposed. The findings were applied to growth of pseudomorphic InGaAs/InAlAs/InP HEMT.

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